APEX simulation of best irrigation and N management strategies for off-site N pollution control in three Mediterranean irrigated watersheds

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Abstract

One of the main constraints of irrigated agriculture is off-site N pollution due to export of nitrate in irrigation return flows (IRF). Models capable of simulating the growth of crops and the N loads in IRF as affected by irrigation and N fertilization may be valuable tools in watershed studies. The Agricultural Policy Environmental eXtender (APEX) model was used to assess best management practices for reducing off-site N loads in the IRF of three Mediterranean irrigated watersheds (Akarsu in Turkey, La Violada in Spain and Sidi Rached in Algeria). The watersheds (ranging from 4013 to 10971 ha) were monitored along three hydrological years to determine the volume of IRF and the NO_3-N concentrations and loads in IRF. APEX was calibrated with the data of the first two years and validated with the last year´s data. APEX adequately simulated crop evapotranspiration and the volume of IRF and N loads in the IRF (errors < 20%). Simulated annual values were in general more accurate than simulated monthly values. APEX predicted that improving irrigation management (change of irrigation system and/or scheduling) will decrease N loads in IRF over current values by 45% (Akarsu), 40% (La Violada), and 8% (Sidi Rached). However, improved N fertilization only will reduce N loads in IRF by 17% (Akarsu) or below 5% (La Violada and Sidi Rached). Improving irrigation management will increase IRF NO_3-N concentrations by 19% in La Violada and will decrease or will remain the same in the other two watersheds. APEX simulations identified the main soils (shallow and low water holding capacity soils) and crops (heavily fertilized or shallow-root crops) N polluters within the studied watersheds. Overall, APEX simulated that the improvement of irrigation performance was the best management strategy to decrease off-site N pollution while maintaining or increasing crop yields in the three studied Mediterranean watersheds.

Keywords: model, nitrogen, pollution, irrigation, fertilizer, watershed

1. Introduction

Irrigation is needed under Mediterranean climatic conditions to obtain profitable crop yields. One of the main constraints of irrigated agriculture is off-site N pollution due to the export of nitrate loads in its irrigation return flows (IRF) (Aragüés and Tanji, 2003; Cavero et al., 2003). Several factors such as the irrigation system (Power et al., 2000), irrigation management (Diez et al., 2000; Martin et al., 1994; Pang et al., 1997; Schepers et al., 1995), N fertilizer management (N rate, application method and splitting) (Diez et al, 2000; Moreno et al., 1996), soil characteristics (Sogbedji et al., 2000), and rainfall patterns conditions (Klocke et al., 1999) influence nitrate leaching and loads in the IRF.

Models can be useful tools for simulating the growth of crops and its consequences in the environment in watershed studies. A myriad of models have been developed in the last decades to simulate nutrient losses at the plot and watershed scales. Borah et al. (2006) provided an extensive revision of watershed models indicating their strengths and weaknesses. Several watershed scale models have been tested to simulate the fate of N (Fernandez et al., 2006; Hu et al., 2007; Huang et al., 2009; Schilling and Wolter, 2009; Sogbedji and McIsaac, 2006; Wang et al., 2009; Yuan et al., 2003). Once validated, these models can be applied to assess best management practices aimed at controlling N loads in IRF (Chaplot et al., 2004; de Paz and Ramos, 2004; Gitau et al., 2004; Wang et al., 2009; Laurent and Ruelland, 2011).

In watersheds where agriculture is preponderant, models must account for all processes affecting the N cycle and, in particular, they must simulate accurately the growth of crops because it determines the N uptake, which is a relevant component of the N cycle. Crop evapotranspiration and irrigation application should be modeled with particular attention in irrigated watersheds. Moreover, models must be capable of simulating different irrigation systems and scheduling strategies and different N fertilizer management (N rates, application methods and N splitting) if different strategies are to be assessed to reduce N loads in IRF.

Agricultural Policy Environmental eXtender (APEX) (Williams and Izaurralde, 2005), Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), and its combination SWAPP (Saleh and Gallego, 2007) are the most detailed watershed models in terms of crop growth and N cycling (Borah et al., 2006). Schilling and Wolter (2009) used SWAT to study different scenarios of N fertilizer reductions considering the complete watershed as well as the most pollutant areas within the watershed. Hu et al. (2007) pointed out that most works with watershed models do not include results about crop yields and the N cycle components, and found some limitations of SWAT on these subjects. Saleh and Gallego (2007) reported the advantages of using APEX instead of SWAT when detailed management cropping practices are assessed.

Most studies with watershed models have been performed in agricultural areas without irrigation. However, in semiarid climates N pollution is mainly derived from irrigated areas (Cavero et al., 2003; Spalding et al., 2001). The objective of this study was to analyze with the APEX model best management practices for reducing off-site N loads in the irrigation return flows of three Mediterranean irrigated watersheds. The APEX model was chosen because of its relative simplicity and capability to simulate different crops, rotations and management alternatives to reduce off-site N pollution (Harman et al., 2004; Osei et al., 2008).

2. Materials and Methods

2.1 Experimental data

2.1.1 Watersheds description

Three irrigated watersheds in the Mediterranean area were studied during three hydrological years (from Oct. to Sept.). They were located in Turkey (Akarsu watershed), Spain (La Violada watershed) and Algeria (Sidi Rached watershed) (Fig. 1). The Akarsu watershed is located in the Mediterranean coastal region, one of the most intensively cropped areas of Turkey, covers an irrigated area of 9495 ha within the Lower Seyhan Plain (36^{o}57′ N, 35^{o}40′ E), and receives water from the Seyhan and Ceyhan rivers. The area has been irrigated for over 40 years with appropriate irrigation and drainage infrastructures consisting mainly of open ditches that evacuate the drainage waters to the Mediterranean Sea. The Akarsu Irrigation Association is responsible for irrigation management in the area. Irrigation efficiency in the area is low (50%), and irrigation management needs to be improved to prevent excess irrigation and decrease drainage discharge (Aragüés et al., 2011).

La Violada watershed is located in the middle Ebro River valley in north-east Spain (41°59’ N, 0°32’ W), covers an irrigated area of 4013 ha, and receives water from the Gallego river. The watershed is surrounded by the Monegros, Santa Quiteria and Violada canals, and has been under irrigation during 80 years. Most of the area is managed by the Almudevar Irrigation Association. The drainage system is composed of a dense network of open ditches and buried pipes flowing into two main open ditches that join into La Violada Gully, the single drainage outlet for this watershed.

The Sidi Rached watershed is located in northern Algeria (36°25’N, 2°32’ E), covers an irrigated area of 10971 ha and receives water from Bouroumi and Boukourdene dams. The irrigation network in the study district has been modernized in the early 2000’s. The flow of water starts in the Atlas mountain chains at more than 600 m height and ends at a drainage outlet at 50 m height.

Mediterranean-type climate prevails in the three study areas, typically with hot and dry summers and mild and rainy winters. The seasonality and irregularity of rainfall and the high summer temperatures promote the need for irrigation mainly during the summer season. Climate data such as precipitation, temperature, wind speed and solar radiation were gathered on a daily basis in automatic meteorological stations established in representative locations within the watersheds. Average values of historical meteorological data for the three watersheds are provided in Table 1.

The main characteristics of the soils found in the different watersheds are given in Table 2. The three soil types at Akarsu are relatively uniform, and have a high water holding capacity due to their high clay contents predominant in swelling smectites. The four soil types at La Violada are heterogeneous, with soil depths ranging from 0.35 m to 1.20 m, coarse fragments ranging from 0 to 50%, and variable water holding capacities. The four soils at Sidi Rached, clay to loamy clay in texture, are very deep and with medium water holding capacities.

2.1.2 Management of crops

The crops grown each year were determined by remote sensing techniques and field surveys in Akarsu, provided by the water user associations (La Violada) or determined from field surveys (Sidi Rached) (Table 3). Maize (*Zea mays* L.), citrus (*Citrus sinensis* (L.) Osbeck) and wheat (*Triticum aestivum* L.) were the main crops at Akarsu watershed. Other crops grown were cotton (*Gossypium hirsutum* L.), maize as second crop after wheat harvest, and melon (*Cucumis melo* L.). At the La Violada watershed, alfalfa (*Medicago sativa* L.) and barley (*Hordeum vulgare* L.) were the main crops occupying about 75% of the area in 2006 and 2007. In 2008, 46% of the area was not cultivated because of the irrigation modernization works taking place in La Violada. Potato (*Solanum tuberosum* L.) and wheat were the main crops at Sidi Rached, occupying 85% of the watershed.

The main irrigation system in Akarsu is surface irrigation, but citrus is mainly irrigated by drip irrigation. Surface irrigation is also preponderant in La Violada. However, drip irrigation is used in two thirds of Sidi Rached. The water distribution systems in these watersheds are composed of a large number of lined and unlined canals and ditches operated 24 h a day, so that farmers have to irrigate during day and night times. Irrigation water amounts (Table 3) and intervals, and N fertilizer amounts (Table 3), fertilizer types and application dates given to each crop were obtained from farmer interviews.

2.1.3 Crop evapotranspiration

Evapotranspiration is one of the most relevant variables of the water balance in irrigated agriculture. Thus, the actual evapotranspiration was calculated for the three hydrological years analyzed in each watershed. First, the reference evapotranspiration (ETo) was calculated with the Food and Agriculture Organization (FAO) Penman-Monteith method (Allen et al., 1998) using the data gathered in the meteorological stations. The potential crop evapotranspiration was calculated as ETo multiplied by Kc, where Kc are the crop coefficients taken from local information or the literature (Allen et al., 1998). Finally, the actual crop evapotranspiration (ETc) was calculated through a daily soil water balance based on soil (field capacity, wilting point and percent coarse fragments) and crop (root depth and depletion fraction) properties. The inputs for the balance were the daily irrigation and precipitation. The daily inputs were added to the soil water content at the beginning of the day and the ETc was calculated as the potential evapotranspiration multiplied by a stress coefficient (Allen et al., 1998), with the excess of water above field capacity at the end of the day being assigned to drainage.

2.1.4 N load in the irrigation return flows

The hydrological year in all watersheds was considered to start on 1st October and end on 30th September of the following year. The irrigation season was from 1st April to 30th September and the rest of the year was considered to be the non-irrigation season.

Precipitation amounts were measured at the automatic meteorological stations located in each watershed. The irrigation return flows (IRF) were measured hourly in gauging stations constructed at the drainage outlet of each watershed. Instantaneous drainage water samples (0.25 L in volume) were taken daily with automatic water samplers installed in the gauging stations. Precipitation and irrigation water samples were taken periodically. The nitrate concentrations in these waters, reported as nitrate nitrogen (NO_3-N), were analyzed colorimetrically with a continuous flow analyzer (AA3, Bran+Luebbe, Norderstedt, Germany).

N load in IRF was calculated daily from the drainage volume and its NO_3-N concentration, and the monthly and yearly N loads were obtained by summing up the corresponding daily values.

2.2 APEX simulations

2.2.1 APEX calibration and validation

APEX calculates daily all the terms of the water balance and the growth of crops after defining homogeneous subareas in terms of climate, soil type and crop management. Given the relatively low acreage of the watersheds, the climate was considered the same within each watershed. Three soil types were defined in Akarsu and four soil types in La Violada and Sidi Rached (Table 2). Since only general information about N fertilizer applications was obtained in Akarsu, they were considered to be the same for each crop. In La Violada and Sidi Rached the interviews allowed to determine the N applied to the crops each year (Table 3).

The irrigation applied in La Violada was not available at the plot level, and it was assumed to be the same for a given area with a given crop and soil type. This was the typical situation reported in farmer's interviews because in surface irrigation the soil type defines the water holding capacity and the irrigation interval. Thus, La Violada was divided into 58 subareas with the same soil-crop rotation-irrigation management. At Akarsu and Sidi Rached the water holding capacities of the different soil types were similar so that the same irrigation depths were considered for each crop in all soil types and the subareas (29 in Akarsu and 7 in Sidi Rached) were defined in terms of the soil-crop rotations.

APEX allows flow routing considering the exact locations of the subareas. However, only one IRF measurement station existed in each watershed and not detailed information was available at the plot level. Consequently, no real location flow routing but just addition of the IRF from the different subareas was simulated. The olive crop grown in La Violada was not simulated because it was not included in APEX. This crop covered less than 2% of La Violada watershed and it was drip irrigated, so low N losses are expected.

The first two hydrological years were used in each watershed for model calibration (2006-2007 in La Violada, and 2007-2008 in Akarsu and Sidi Rached) and the last hydrological year (2008 in La Violada and 2009 in Akarsu and Sidi Rached) was used for model validation. The monthly and annual volumes of water and nitrate loads measured in the IRF of each watershed were compared with APEX simulations for calibration. Arnold and Allen (1996) indicated that in order to validate a watershed model, several hydrological components should be tested. Thus, annual evapotranspiration and average N concentration in the IRF were used to test model performance.

2.2.2 APEX application: best management practices aimed at reducing N loads in IRF

APEX was used to assess the contributions of crops and soils and the effects of best management practices on N concentrations and loads in the IRF of the three watersheds. Four scenarios were tested: 1) current scenario, 2) improved irrigation, 3) improved N fertilization, and 4) improved irrigation and N fertilization. The three improved scenarios differed in each watershed because they were designed on the basis of its particular constraints and inefficiencies in terms of irrigation and N fertilization management. The APEX model was run for the same hydrological years used in the calibration and validation steps.

At Akarsu the improved irrigation scenario consisted in changing from surface to sprinkler irrigation in maize, cotton and melon. This change allowed to apply irrigation as required by crops. The required irrigation depths were calculated from the ETc of each crop minus the effective precipitation (75% of precipitation). The calculations were made weekly and the required irrigation depths were applied in one or two irrigations per week. Irrigation depths ranged generally from 10 to 30 mm per irrigation event. The improved N fertilization scenario consisted in applying the N fertilizer at optimum rates in maize, maize second crop, and wheat (Table 4). The optimum N rates were derived from local studies and the literature. The improved irrigation and N fertilization scenario consisted in the combination of the individual scenarios described above.

At La Violada the improved irrigation consisted in changing from surface to sprinkler irrigation in all crops, which is the actual modernization taking place in this watershed. This change allowed to apply irrigation as needed by each crop. The required irrigation was calculated similarly to the Akarsu watershed. The improved N fertilization consisted in applying the N fertilizer at optimum rates for the different crops (Table 4). In some crops as maize, alfalfa and pepper the N applied was reduced, while in others as barley, wheat, sunflower and ryegrass it was increased because farmers surveys showed that the amount of N applied was below the optimum level. These optimum N rates were derived from local studies and the literature. The improved irrigation and N fertilization scenario consisted in the combination of the individual scenarios described above.

At Sidi Rached the improved irrigation scenario consisted in that the required irrigation in citrus and grapes was automatically scheduled following the FAO CROPWAT model (Smith, 1992) using the following criteria: irrigation started at 40 mm soil water depletion and the irrigation depth applied was that needed to refill the soil to field capacity. The improved N fertilization consisted in reducing the N fertilizer applied by 50% in all crops except citrus (Table 4).

3. Results

3.1 APEX calibration and validation

Two parameters were most relevant in the APEX calibration step: the RFPO (return flow proportion), an empirical parameter that defines the proportion of the water percolating below the crop’s root zone that is intercepted by the drainage network and exits each subarea as IRF, and the RTF0 (groundwater residence time), an empirical parameter that defines the time needed for the percolating waters to arrive to the drainage network. They are related to hydrological characteristics of the watershed. The simulated IRF and N load in IRF are very sensitive to the value used for these parameters (Wang et al., 2006). Thus, both parameters were iteratively modified for the best possible adjustments of APEX-simulated and measured IRF and N load in IRF. The RFPO values used for the different watersheds were 0.80 (Akarsu), 0.90 (La Violada) and 0.53 (Sidi Rached). The RTF0 values used for the different watersheds were 30 days (Akarsu), 45 days (La Violada) and 50 days (Sidi Rached).

3.1.1 Akarsu watershed

APEX simulated annual ETc within ±8% of calculated values in the calibration step and underestimated ETc by 15% in the validation step (Table 5). The discrepancy between observed and APEX-simulated annual IRF was around ±20% in the calibration and validation steps, whereas the discrepancy for the annual N loads were -8% and +27% in the calibration years and +21% in the validation year (Table 5). However, the discrepancy between observed and simulated values of annual N concentration in the IRF ranged from -33% to +51%. When considering the mean values for the three hydrological years, the discrepancy between observed and simulated values was -6% for ETc, +8% for IRF, -8% for N concentration in IRF and -5% for N loads in IRF.

The monthly APEX-simulated IRF and N loads were generally close to the observed values showing a percent bias lower than 25% (Table 6). However, N loads in the validation year were underestimated during the non-irrigation season and overestimated during the July to September irrigation months (Fig. 2). Thus, the regressions between the simulated and observed monthly N loads were not significant ($P>0.05$) (Table 6) showing that APEX did not behave properly at the monthly basis for this variable.

In terms of soils and crops, APEX simulated that the highest N losses in IRF occurred in the Arikli soil and in maize, melon and cotton, whereas the lowest N losses occurred in the Yenice soil and in wheat, maize-second crop and citrus (Table 7).

3.1.2 La Violada watershed

APEX accurately simulated annual ETc and IRF within ±4% of measured values, except IRF in the validation year that was overestimated by 15%. The annual N concentration and N load in IRF errors were higher (±25%), but given its low values the discrepancies between observed and simulated values of N load in IRF were only 5 kg N ha^{-1} or lower (Table 5). It should be highlighted that even though ETc, IRF and N loads in IRF were much lower in 2008, APEX was able to simulate them properly, with errors of -4% (ETc), +15% (IRF), +7% (N concentration) and +25% (N load) (Table 5). When considering the mean values for the three hydrological years, the discrepancies between observed and simulated values were negligible (Table 5).

APEX-simulated and measured monthly values were quite close (Table 6), although IRF and N loads were overestimated in some months of the 2008 irrigation season (Fig. 3). The regressions between the simulated and measured monthly IRF and N loads were significant ($P < 0.05$) and only the slope of IRF for the calibration period was different from 1 (Table 6).

APEX-simulated N losses were much higher in soil type A (due to its lower depth and water holding capacity, Table 2) than in soils C and D that occupy the largest area of the watershed (Table 7). Among the different crops, maize and pepper had the maximum N losses due to high N applications in maize (about 300 kg N ha^{-1}) and shallow rooting depths in pepper.

3.1.3. Sidi Rached watershed

APEX overestimated annual ETc by more than 20% in the three hydrological years (Table 5). As expected in a watershed where drip irrigation is preponderant, IRF were much lower than in Akarsu and La Violada. Annual IRF were accurately estimated in the two calibration years (-6%), but not in the validation year (+31%). Annual N concentration in IRF was only accurately simulated in one of the calibration years (2008). Annual N load in IRF was accurately estimated in 2008 (+8%) and reasonably estimated in 2009 (-17%), but not in 2007 (-45%). Given the relatively low N loads, these errors were equivalent to differences of 5 kg ha^{-1} or lower. When considering the mean values for the three hydrological years, the discrepancies between observed and simulated values were +24% for ETc, +11% for IRF, -22% for N concentration in IRF and -19% for N loads in IRF (Table 5).

APEX-simulated and measured monthly IRF and N loads were close in the three hydrological years except for the IRF in the validation year that had a percent bias of 30% (Figure 4, Table 6). The regressions between simulated and measured monthly IRF and N loads were significant ($P<0.01$) and with slopes not different from 1 (Table 6), showing that APEX was able to properly simulate these monthly values.

In general, simulated N losses were higher in soil type I and lower in soil type III (Table 7) due to its higher water holding capacity. The largest simulated N losses were found in grapes and wheat-potato, although all values were below 20 kg ha^{-1} due to the low IRF typical in drip-irrigated systems.

3.2 APEX application: best management practices aimed at reducing N loads in IRF

3.2.1 Akarsu watershed

APEX simulations indicate that the improved irrigation management scenario (change from surface to sprinkler irrigation in maize, cotton and melon) would allow to reduce the irrigation applied by 14%, while increasing ETc by 4% (Table 8). IRF will be reduced by 22%, N concentration in IRF by 30% and N load in IRF by 45% (Table 8). APEX simulations indicate that improving irrigation management would increase the yield of cotton by 25%, while no improvements were found for the rest of crops (data not given). Considering the different crops, improvement in irrigation management would reduce N losses by more than 50% in all crops, except in maize as second crop (Table 9).

The improved N fertilization scenario (optimum N rates in maize and wheat) would reduce the N concentration in IRF by 20% and the N load in IRF by 17% from values in the current scenario (Table 8). The improved N fertilization scenario had no effect on crop yields (data not given), but it was very relevant to reduce N losses in maize (Table 9).

In relation to the current scenario, the combination of improved irrigation and N fertilization will reduce the N concentration in IRF by 35%, the N load in IRF by 48% (Table 8) and the N losses by 60% in maize and 31% in maize as second crop (Table 9).

3.2.2 La Violada watershed

APEX simulations indicate that the improved irrigation management scenario (change from surface to sprinkler irrigation in all crops) would allow to reduce the irrigation applied by 12%, while increasing ETc by 15% (Table 8). Consequently, IRF will be reduced by 48% and N load in IRF by 40%, whereas N concentration in IRF will increase by 19% (Table 8). The monthly N loads were lower and the monthly N concentrations higher than in the current scenario, with the highest increases in N concentration in IRF occurring in the irrigated seasons of the three studied years (Fig. 5). Hence, the threshold N concentration of 10 mg NO_3-N L^{-1} for human consumption was exceeded in 5 months in the current scenario and in 11 months in the improved irrigation scenario (Figure 5). APEX simulations indicate that the change from surface to sprinkler irrigation would increase yields in alfalfa (18%), barley (9%), maize (15%), ryegrass (34%), sunflower (30%) and wheat (15%) (data not given) and would reduce the N losses by more than 50% in most crops (Table 9).

The improved N fertilization scenario (optimum N applications to all crops) would reduce the N load in IRF only by 3% and will not change the N concentration in IRF (Table 8), will have a negligible effect on crop yields (data not given) and will reduce N losses in alfalfa but not in the other crops. Moreover, this scenario increased the N losses in crops where N applications increased over those in the current scenario (barley, ryegrass, sunflower and wheat) (Table 9).

The combination of improved irrigation and N fertilization management produced similar IRF, N concentration in IRF and N load in IRF than in the improved irrigation scenario (Table 8), increased yields in barley (10%), ryegrass (43%), sunflower (40%) and wheat (20%), and significantly reduced N losses in alfalfa but not in the rest of crops in relation to respective losses in the improved irrigation scenario (Table 9).

3.2.3 Sidi Rached watershed

APEX simulations indicate that the improved irrigation management scenario (citrus and grapes irrigated following the FAO CROPWAT model) would have similar irrigation and ETc values than the current scenario. Therefore, changes in IRF, N concentration in IRF and N load in IRF over those in the current scenario were also low (-3%, -4%, and -8%, respectively) (Table 8), although N loads will be reduced by 27% in citrus and by 12% in grapes (Table 9).

The improved N fertilization scenario (50% reduction in N applied to all crops) would reduce the N concentration and load in IRF by 5% (Table 8), whereas N losses will be reduced only by 3% in all crops in relation to those in the current scenario (Table 9).

The improvement of both irrigation and N fertilization management would reduce the N concentration in IRF by 7% and the N load in IRF by 12% over those in the current scenario (Table 8). Crop yields remained the same in all simulated scenarios (data not given).

4. Discussion

4.1 APEX calibration and validation

ETc is generally the main water output in irrigated agriculture. Thus, APEX should simulate it accurately for a correct prediction of IRF and N loads in IRF. Testing the accuracy of ETc simulations at the watershed scale is difficult because there are not practical methods for its measurement in multicrop agricultural watersheds. We calculated ETc with a daily soil water balance for each crop and soil type to get actual rather than potential values, but this approach estimates rather than measures ETc. Taking this limitation into account, ETc estimates using APEX were considered satisfactory in Akarsu and La Violada (errors < 15%, Table 5) (Singh et al., 2006) and poor in Sidi Rached (errors > 20%). Hence APEX simulations in the Sidi Rached watershed should be taken with caution.

APEX simulations of hydrological year IRF and N loads in IRF were considered satisfactory in the three watersheds (discrepancies between calculated and estimated values close or lower than 20% in 13 out of the 18 simulations, Table 5) (Moriasi et al., 2007). However, APEX simulations of hydrological year N concentrations in IRF were not so accurate in Akarsu. APEX simulations of monthly IRF and N loads in IRF were generally close to observed values, except in some irrigation months of the validation years (Figs. 2-4), resulting in a relatively high RMSE and low R^2 in some cases, but with a percent bias generally lower than 25% (Table 6) than can be considered satisfactory (Moriasi et al., 2007). Monthly values of IRF were in general better simulated than monthly N loads in IRF, a result similar to that of Hu et al. (2007). Hence, yearly simulations were more reliable than monthly simulations. Moreover, mean values of the three hydrological years for all the variables (ETc, IRF, N concentration in IRF and N load in IRF) were simulated with errors lower than 9% (Akarsu), 2% (La Violada), and 25% (Sidi Rached). Bora and Bera (2004) and Sogbedji and McIsaac (2006) also found more accurate simulations with increased time scales.

Even though the APEX-simulated annual estimates were adequate in general, several reasons may explain some discrepancies with measured values: a) the mean irrigation depths and mean N fertilizer rates inputs to APEX did not take into account the existence of higher values at given times that contributed most to water and N losses, b) water contributions from groundwaters that are difficult to model (hence, the interaction of drainage waters with shallow groundwater tables (≈ 1.5 m) present in the low-lying areas of Akarsu could partially explain the discrepancies), and c) lack of consideration by APEX of irrigation uniformities (Cavero et al., 2001; Dechmi et al., 2010).

APEX simulations identified those soils and crops where N losses were higher. This is a relevant APEX ability because, as shown by Schilling and Wolter (2009), the identification of the main soil and crop polluters within a watershed is a needed prerequisite to efficiently reduce N loads in IRF. Recently, Laurent and Ruelland (2011) have used SWAT to identify the soils and crops where N losses were higher in a non irrigated watershed. There were only slight differences among the simulated N losses found in the different Akarsu soils due to their high water holding capacities. In contrast, APEX predicted much higher N losses in soils A (La Violada) and I (Sidi Rached) with lower soil water holding capacities than the rest of soils in these watersheds. In terms of crops, APEX predicted that the higher N polluters were maize, cotton and melon at Akarsu, maize and pepper at La Violada, and grapes and potato at Sidi Rached. Maize (Cavero et al., 2003; Diez et al., 1996; Isidoro et al., 2006) and shallow-rooted vegetables (de Paz and Ramos, 2001; Ramos et al., 2002; Vazquez et al., 2006) have been found also to be major contributors to N loads in other irrigated areas.

4.2 APEX application: best management practices aimed at reducing N loads in IRF

APEX is an effective tool to assess best management practices for reducing N loads in IRF because of its detailed agronomic simulations (Borah et al., 2006). Improved irrigation performance in the three watersheds was simulated by APEX as the best strategy to reduce N loads. These reductions amounted to 40-45% in the surface-irrigated Akarsu and La Violada watersheds, similar to those found by Diez et al. (2000) in a Mediterranean irrigation district, but only to 8% in the more efficient drip-irrigated Sidi Rached watershed. The relevance of the irrigation system and its management for off-site N pollution control has been pointed out in several works where lower N losses were found in efficient pressurized irrigation systems with typical low IRF, and higher losses in inefficient surface irrigation systems with typical high IRF (Causapé et al., 2006; Cavero et al., 2003; Klocke et al., 1999; Power et al., 2000; Spalding et al., 2001).

APEX simulations showed that improved N fertilization was less efficient in reducing N loads in IRF than improved irrigation performance (N load reductions of 17% in Akarsu and less than 5% in La Violada and Sidi Rached). Similar results were obtained by Power et al. (2000) and Smika et al. (1977). A similar impact of improved N management was found by Gowda et al. (2008), but higher reductions in N loads were found by Mitchell et al. (2000). Laurent and Ruelland (2011) simulated a 15% N load reduction with reduced fertilization in a non irrigated watershed with SWAT.

In agreement with these results, APEX simulations in the improved irrigation and fertilization scenario indicate that the benefits in decreasing N loads were similar to the improved irrigation scenario. Hence, irrigation performance rather than N fertilization performance is the critical management practice to reduce N loads in the IRF of the three studied watersheds.

In terms of crops, APEX simulations showed that improving irrigation management will reduce the percent N losses similarly in all crops, while improving N fertilization will be only effective in those crops highly over fertilized (maize in Akarsu and alfalfa in La Violada) (Chaplot et al., 2004; Laurent and Ruelland, 2011) or shallow-rooted (pepper in La Violada).

One important advantage of APEX is that it also simulates crop yields. This allows finding those management practices that would decrease N loads in IRF without affecting yields (Hu et al., 2007; Power et al., 2000). APEX predicted that improved irrigation management in Akarsu and La Violada will decrease the applied irrigation by 12-14%, will increase ETc by 4-15%, and will increase yields by 9-34% in all crops. These results agree with the well established relationship between increased evapotranspiration and increased yield (Howell, 1990). In the case of Sidi Rached, the improved irrigation scenario did not result in significant increases in ETc and yields, probably because drip irrigation management was already adequate to meet crop water needs.

APEX simulations predicted that, although improved irrigation management will always decrease N loads in IRF, NO_3-N concentrations could decrease (Akarsu, -30% compared to the current scenario), increase (La Violada, +19%) or remain almost unchanged (Sidi Rached, -4%). Lower IRF and N loads in IRF and higher NO_3-N concentrations in IRF have been found in sprinkler compared to surface irrigated areas (Cavero et al., 2003; Causapé et al., 2006). The rational hypothesis supporting that improved irrigation performance decreases IRF and N loads but may negatively increase NO_3-N concentrations in IRF has been documented in several studies (Lecina et al., 2010) but this hypothesis is "ambient-dependent" and may be affected by other factors such as the irrigation system, soils, hydrogeology, climate and cropping patterns (Cambardella et al., 1999; Cavero et al., 2003).

5. CONCLUSIONS

1) The APEX model, calibrated and validated in three Mediterranean irrigated watersheds along three hydrological years, provided adequate simulations for the annual volume of irrigation return flows (IRF) and its N loads. The monthly IRF and N load estimates were close in general to the measured values but, overall, this time scale was less reliable than the hydrological year time scale.
2) The high discrepancy (25%) between estimated and simulated ETc in the Sidi Rached watershed indicated that the model predictions for this watershed should be taken with caution.
3) APEX simulated that irrigation improvement was the best management option to reduce N loads in the IRF of the three studied watersheds. In contrast, N

fertilization improvement was much less efficient. In consequence, the combination of improved irrigation and N fertilization provided insignificant N load decreases compared to the improved irrigation scenario.

4) Improved irrigation decreased the irrigation applied and increased the ETc and the yield of several crops in two of the studied watersheds. Hence, this strategy was able to reduce off-site N pollution in these watersheds while maintaining or increasing crop yields.
5) APEX simulations properly identified the main soil and crop N polluters within the studied watersheds. Soils with relatively low water holding properties and crops heavily fertilized or with shallow rooting depths should be targeted to improve its management in order to minimize N loads in drainage waters.
6) APEX simulations indicated that the improvement in irrigation performance could increase, decrease, or maintain unchanged the NO_3-N concentrations in the IRF.
7) APEX simulations could be used for an economic cost benefit analysis of improving the irrigation management that considers the benefits of reducing N pollution.

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8. FIGURE CAPTIONS

Figure 1. Localization within the Mediterranean Basin of the Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) irrigated watersheds.

Figure 2. Measured and APEX-simulated monthly values of the volume and N load in the irrigation return flows of the Akarsu (Turkey) watershed for the calibration (October 2006-september 2008) and validation (October 2008-september 2009) years.

Figure 3. Measured and APEX-simulated monthly values of the volume and N load in the irrigation return flows of La Violada (Spain) watershed for the calibration (October 2005-september 2007) and validation (October 2007-september 2008) years.

Figure 4. Measured and APEX-simulated monthly values of the volume and N load in the irrigation return flows of Sidi Rached (Algeria) watershed for the calibration (October 2006-september 2008) and validation (October 2008-september 2009) years.

Figure 5. APEX-simulated monthly values of NO_3-N loads and concentrations in the irrigation return flows of La Violada (Spain) watershed in the different scenarios along the October 2005 to September 2008 study period. The dashed line at 10 mg NO_3-N L^{-1} shows the threshold N concentration for human consumption.

Table 1. Climatic characteristics (historic annual average values) of Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds.

	Watershed		
	Akarsu	La Violada	Sidi Rached
Mean temperature (ºC)	18.9	13.8	18.6
Maximum temperature (ºC)	31.0	19.8	22.8
Minimum temperature (ºC)	9.0	7.8	14.3
Precipitation (mm)	644	438	564
Reference evapotranspiration (mm)	1538	1166	1254

Table 2. Area occupied and main characteristics of the different soil types in Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds.

Watershed and soil type	Area (ha)	Soil Depth (m)	Coarse fragments (%)	Field Capacity ($m^3\ m^{-3}$)	Wilting Point ($m^3\ m^{-3}$)
Akarsu					
Arikli	3988	0.90	0	0.420	0.230
Incirlik	3608	0.90	0	0.440	0.270
Yenice	1899	0.90	0	0.410	0.280
Total irrigated	9495				
La Violada					
A	431	0.35	50	0.070	0.042
B	259	0.82	30	0.144	0.056
C	2181	1.10	28	0.242	0.094
D	1142	1.20	6	0.308	0.189
Total irrigated	4013				
Sidi Rached					
I	3634	3.00	0	0.290	0.170
II	3372	3.00	0	0.290	0.180
III	2353	3.00	0	0.350	0.190
IV	1612	3.00	0	0.370	0.230
Total irrigated	10971				

Table 3. Area occupied (in percent of total) by each crop in each study year and nitrogen and irrigation applied to the main crops in Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds.

Watershed and crop	Area (%)				N applied	Irrigation
	2006	2007	2008	2009	(kg ha^{-1})	(mm)
Akarsu						
Citrus		26	29	26	180	870
Cotton		9	8	6	180	695
Maize		30	40	29	340	870
Maize (second crop)		8	1	15	325	460
Melon		1	5	3	130	760
Wheat		34	18	36	195	
La Violada						
Alfalfa	45	39	23		40-99	700-1200
Barley	29	39	20		78-111	200-300
Maize	8	7	2		267-324	700-1200
Pepper	1	1			188	700-900
Rice	1	1			90-110	1100
Ryegrass	2	2	3		92-202	300-400
Sunflower	2		1		32-71	300-400
Wheat	4	4	4		78-111	200-300
Olive	2	2	1		53	600
Uncultivated	6	5	46			
Sidi Rached						
Citrus		4	4	4	120-158	450-570
Grapes		8	8	8	158	495
Pasture		3	3	3		
Potato		48	25	48	200	120-245
Potato (late)			29	15	200	255-325
Wheat		37	31	22	183	

Table 4. Nitrogen applied in the improved fertilization scenario in Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds to crops where N applications were changed from the current scenario.

Watershed and crop	N applied (kg ha^{-1})
Akarsu	
Maize	250
Maize (second crop)	220
Wheat	150
La Violada	
Alfalfa	0
Barley	135
Maize	250
Pepper	150
Ryegrass	170
Sunflower	90
Wheat	135
Sidi Rached	
Grapes	79
Potato	100
Potato (late)	100
Wheat	92

Table 5. Observed (Obs), APEX-simulated (Sim) and errors (Err) of annual crop evapotranspiration (ETc), irrigation return flows (IRF), and NO_3-N concentrations (N conc.) and loads in the IRF of Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds for the calibration (C) and validation (V) hydrological years. The average values for the three years are also shown.

Watershed and period	ETc			IRF			N conc. in IRF			N load in IRF		
	Obs	Sim	Err[1]	Obs	Sim	Err	Obs	Sim	Err	Obs	Sim	Err
	(mm)		(%)	(mm)		(%)	(mg L^{-1})		(%)	(kg ha^{-1})		(%)
Akarsu												
2006-2007 (C)	652	706	8	373	459	23	9.5	7.8	-18	38	35	-8
2007-2008 (C)	779	715	-8	440	361	-18	6.1	9.2	51	26	33	27
2008-2009 (V)	845	715	-15	460	554	20	10.4	6.9	-33	48	38	-21
2006-2009	759	712	-6	424	458	8	8.7	8.0	-8	37	35	-5
La Violada												
2005-2006 (C)	638	643	1	292	292	0	6.6	7.2	9	19	21	11
2006-2007 (C)	574	597	4	360	345	-4	6.7	5.4	-19	24	19	-21
2007-2008 (V)	482	463	-4	162	186	15	7.5	8.0	7	12	15	25
2005-2008	565	568	0	271	274	1	6.9	6.9	0	18	18	0
Sidi Rached												
2006-2007 (C)	564	726	29	64	63	-2	16.7	10.1	-40	11	6	-45
2007-2008 (C)	575	705	23	82	77	-6	15.9	18.3	15	13	14	8
2008-2009 (V)	623	754	21	118	154	31	19.8	12.6	-36	23	19	-17
2006-2009	587	728	24	88	98	11	17.5	13.7	-22	16	13	-19

[1]Err = 100 (Sim-Obs)/Obs

Table 6. Mean monthly values of observed (Obs) and APEX-simulated (Sim) irrigation return flows (IRF) and N loads in the IRF of Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds for the calibration (C) and validation (V) hydrological years. RMSE = root mean square error of differences between observed and simulated values. Pbias = percent bias. R^2 (coefficient of determination) and slope of the regressions between simulated and observed values.

Watershed and hydrological year	IRF						N load in IRF					
	Obs	Sim	RMSE	Pbias	R^2	slope	Obs	Sim	RMSE	Pbias	R^2	slope
	------ (mm) ------			(%)			----- (kg ha^{-1}) -----			(%)		
Akarsu												
2006-2008 (C)	34.1	34.2	16.7	-0.3	0.54	0.67	2.6	2.9	2.7	-8.6	0.02	0.25
2008-2009 (V)	38.3	46.1	25.3	-20.4	0.26	0.50	4.0	3.2	3.8	19.7	0.01	0.03
La Violada												
2005-2007 (C)	27.2	26.5	14.0	2.5	0.57	0.65	1.8	1.6	0.8	8.9	0.56	0.76
2007-2008 (V)	13.5	15.5	8.5	-14.7	0.75	1.28	1.0	1.2	1.1	-22.2	0.35	1.17
Sidi Rached												
2006-2008 (C)	6.1	5.8	3.4	4.0	0.71	0.88	1.0	0.8	0.7	14.1	0.55	1.02
2008-2009 (V)	9.8	12.8	6.9	-30.5	0.67	0.99	1.9	1.6	1.0	16.9	0.44	0.69

Table 7. APEX-simulated mean values for the three studied hydrological years of N loads in the irrigation return flows (IRF) of Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds for the different crops and soil types.

Crop	N load in IRF (kg ha^{-1})										
	Akarsu (soil type)			La Violada (soil type)				Sidi Rached (soil type)			
	Arikli	Incirlik	Yenice	A	B	C	D	I	II	III	IV
Alfalfa				76	38	8	3				
Barley				79	35	8	3				
Citrus	27		8						4	3	
Cotton	63	50	36								
Grapes								19			
Maize	85	69	61	248	149	47	20				
Maize (second crop)	22	12	13								
Melon	74	86	56								
Pepper				160	113	42	23				
Ryegrass				48	8	2	1				
Sunflower				93	62	22	6				
Wheat	12	10	11	81	30	7	2				1
Wheat-potato								14	8	5	

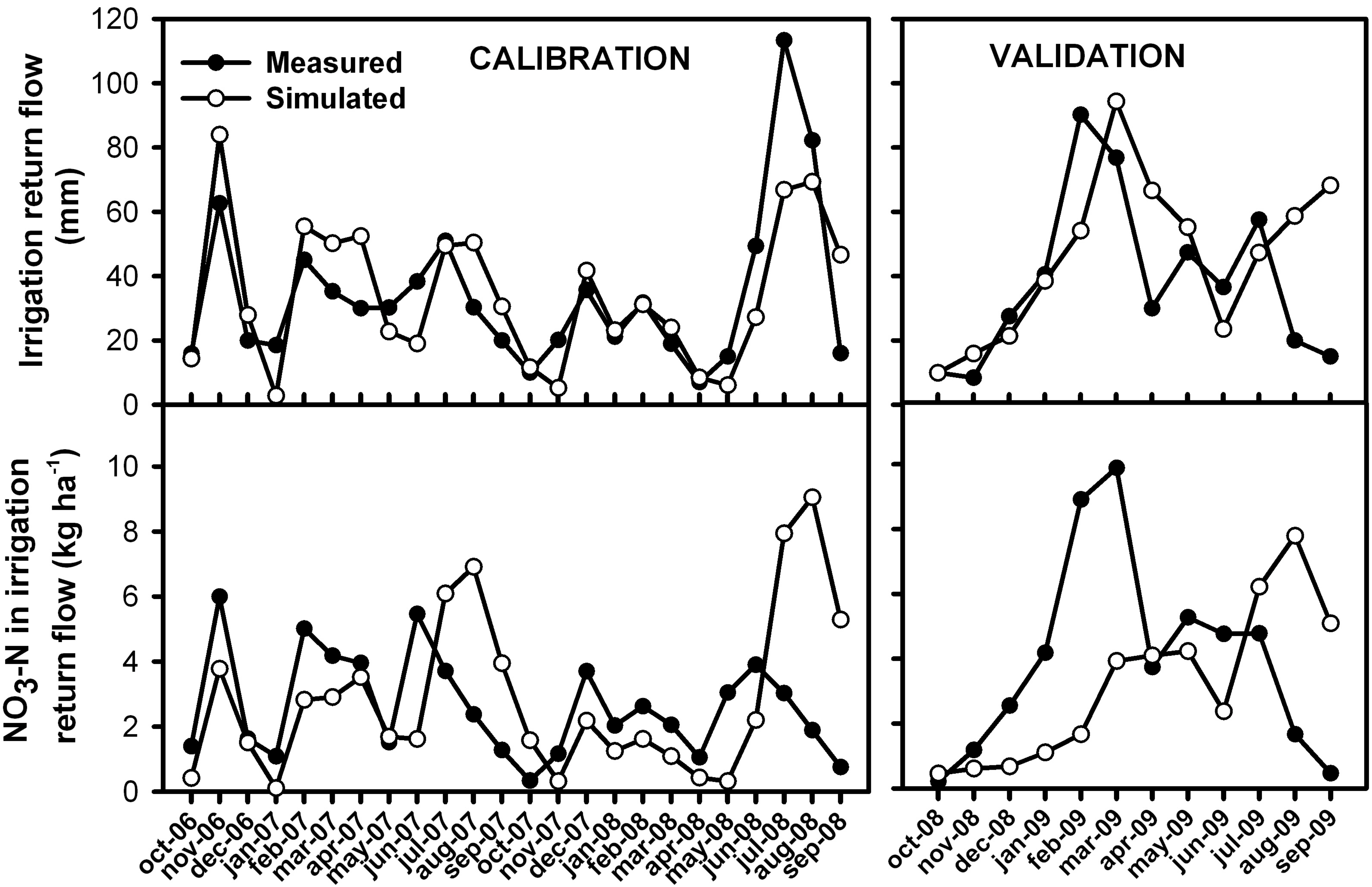
Table 8. APEX-simulated mean values for the three studied hydrological years of irrigation (Irrig), crop evapotranspiration (ETc), irrigation return flows (IRF), NO_3-N concentration (Conc) and N loads in the IRF for the different scenarios assessed in the Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds.

Watershed and scenario	Irrig	ETc	IRF	N in IRF Conc.	N in IRF Load
		(mm)		(mg L^{-1})	(kg ha^{-1})
Akarsu					
Current	634	712	458	8.0	35.6
Improved irrigation	544	740	357	5.6	19.6
Improved N fertilization	634	712	458	6.4	29.4
Improved irrigation + improved N fertilization	544	740	357	5.2	18.4
La Violada					
Current	453	568	274	6.9	18.2
Improved irrigation	400	654	141	8.2	11.0
Improved N fertilization	453	568	274	6.8	17.6
Improved irrigation + improved N fertilization	400	654	139	8.3	10.9
Sidi Rached					
Current	207	728	98	13.7	13.3
Improved irrigation	213	730	95	13.2	12.2
Improved N fertilization	207	728	98	13.0	12.6
Improved irrigation + improved N fertilization	213	730	95	12.7	11.7

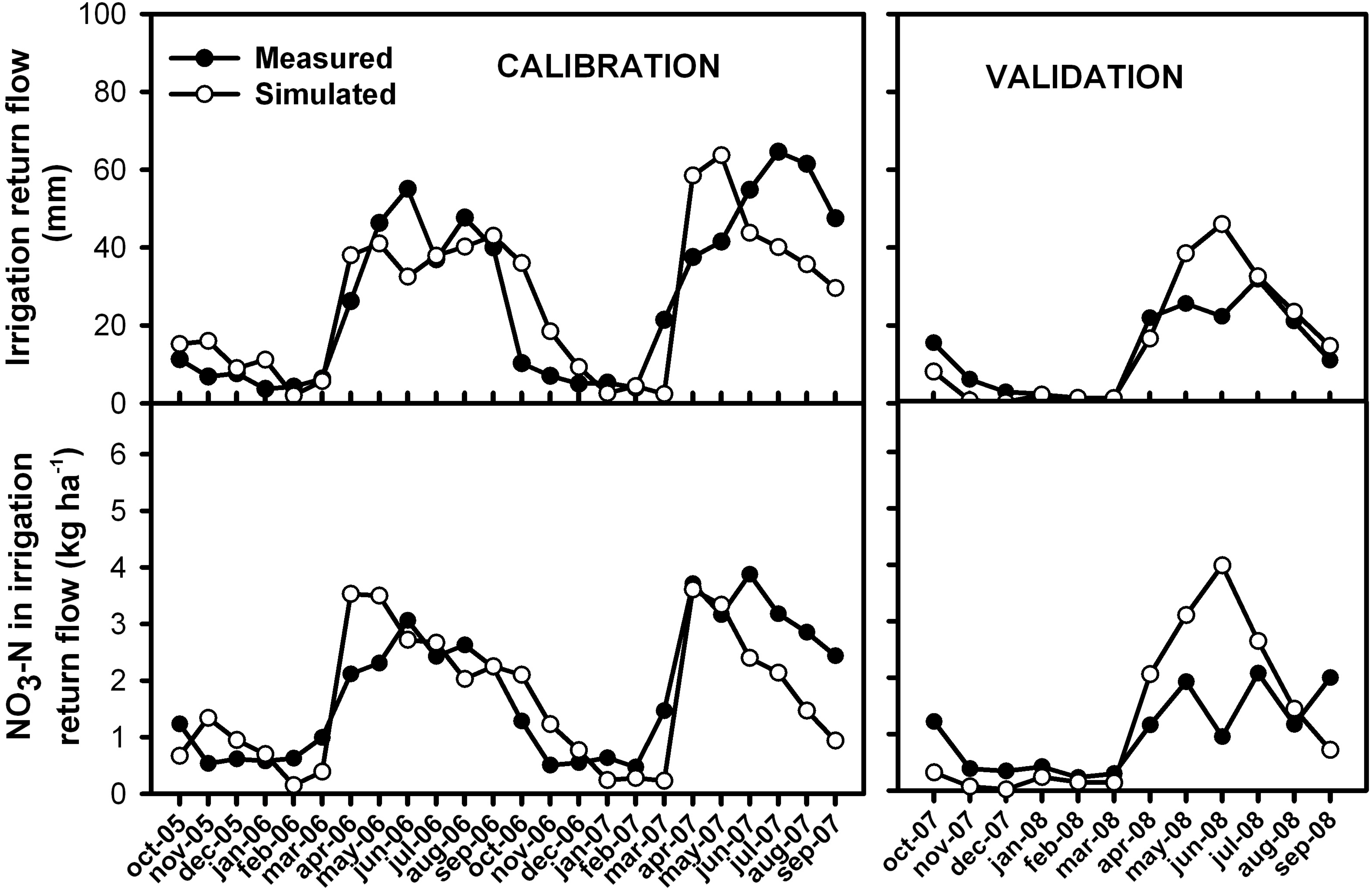
Table 9. APEX-simulated mean values for the three studied hydrological years of N loads in the irrigation return flows (IRF) of Akarsu (Turkey), La Violada (Spain) and Sidi Rached (Algeria) watersheds for the different crops and scenarios analyzed.

Watershed and crop	N load in IRF (kg ha^{-1})			
	Current	Improved irrigation	Improved N fertilization	Improved irrigation and N fertilization
Akarsu				
Cotton	53	22		
Maize	75	35	53	30
Maize (second crop)	16	13	13	11
Melon	75	41		
Wheat (non irrigated)	11		10	
La Violada				
Alfalfa	16	7	8	3
Barley	16	10	22	13
Maize	67	30	60	27
Pepper	55	19	37	17
Ryegrass	7	3	16	4
Sunflower	27	12	31	13
Wheat	15	9	19	11
Sidi Rached				
Citrus	3.7	2.7		
Grapes	19.2	16.9	18.7	18.0
Potato	9.0		8.7	
Wheat (non irrigated)	7.5		7.3	

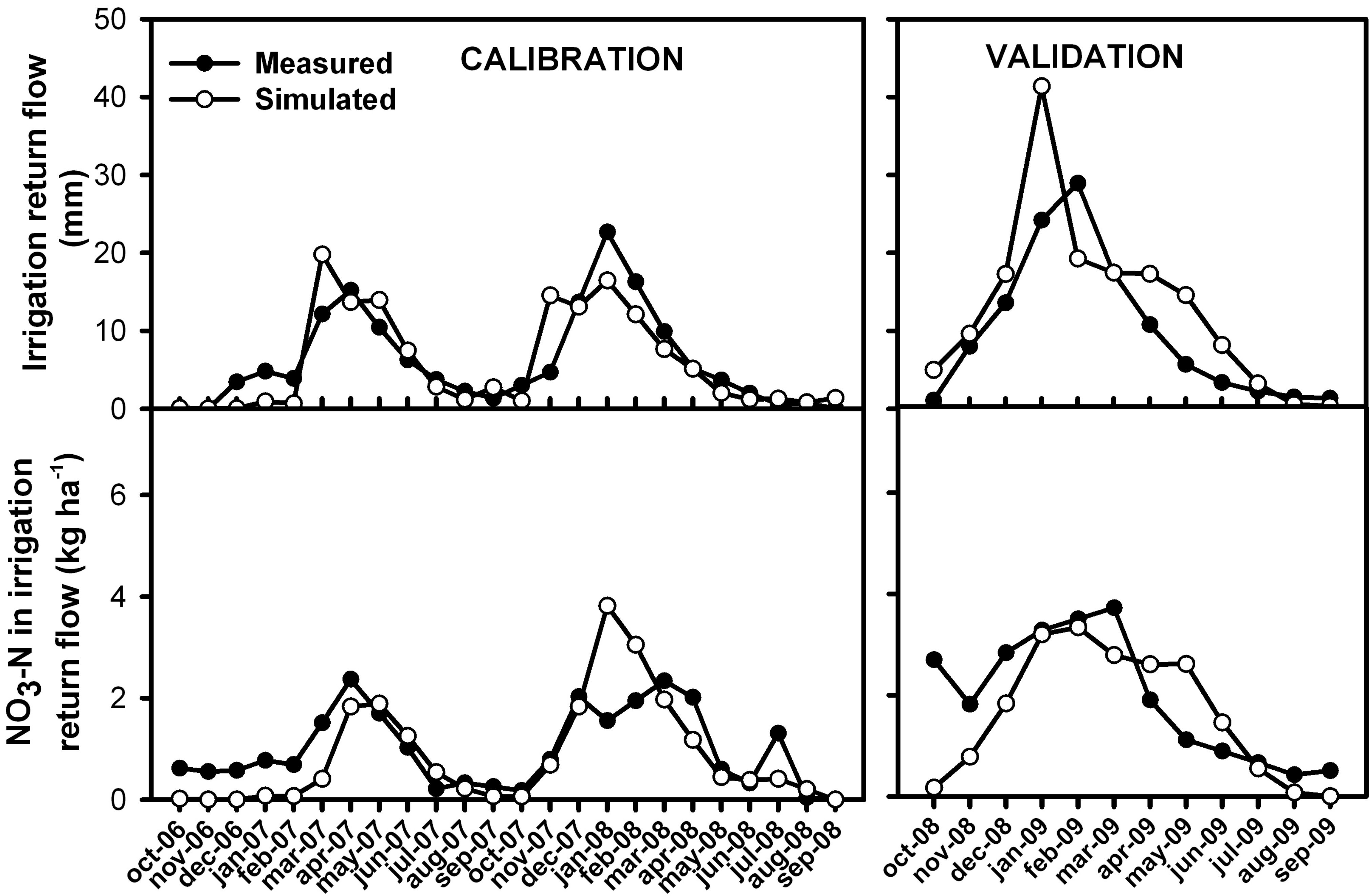

Spain
La Violada
Turkey
Mediterranean
Basin
Sidi Rached
Akarsu
Algeria



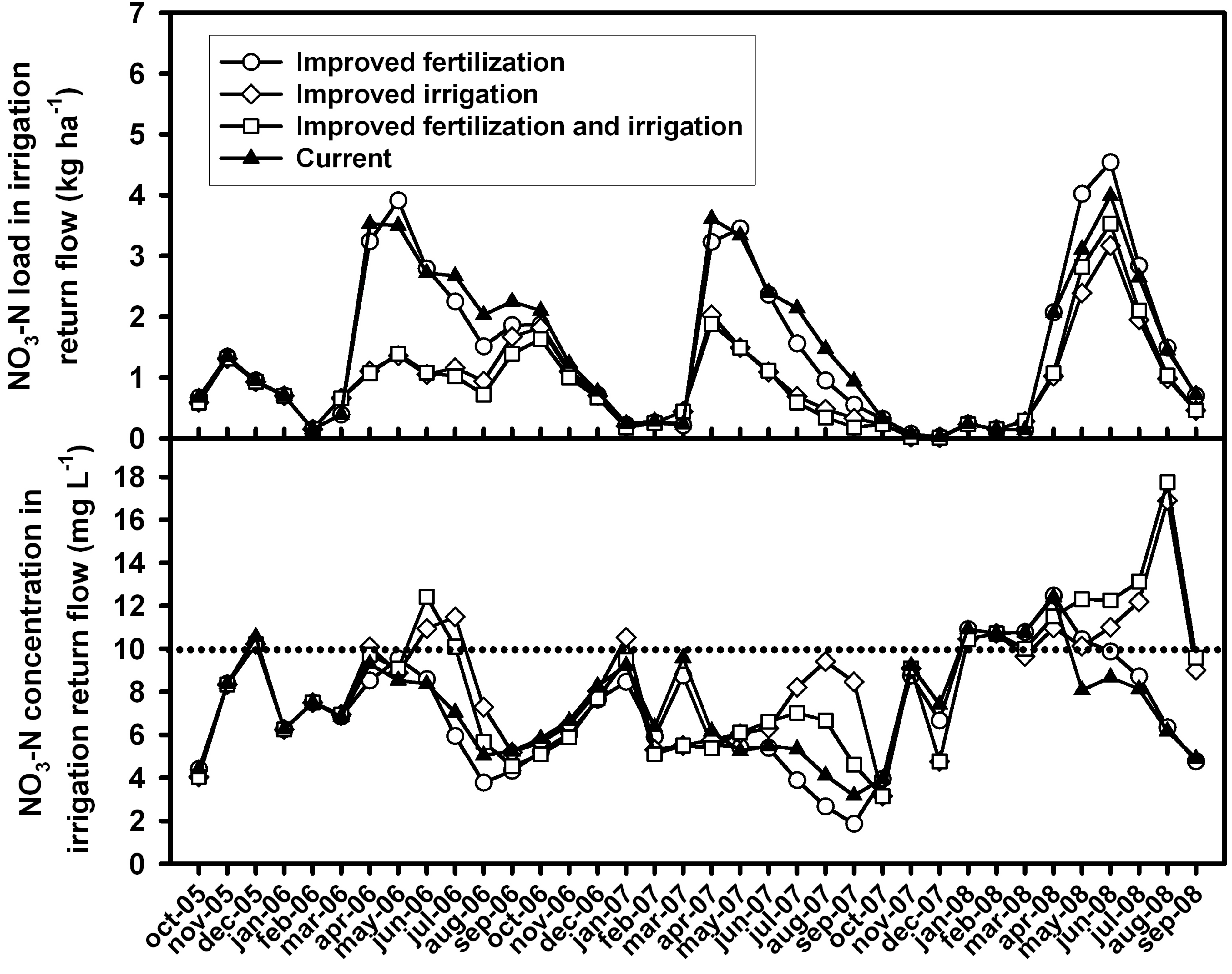
Measured
Simulated
CALIBRATION
VALIDATION
Irrigation return flow (mm)
NO_3-N in irrigation return flow (kg ha^{-1})
120
100
80
60
40
20
0
10
8
6
4
2
0
oct-06 nov-06 dec-06 jan-07 feb-07 mar-07 apr-07 may-07 jun-07 jul-07 aug-07 sep-07 oct-07 nov-07 dec-07 jan-08 feb-08 mar-08 apr-08 may-08 jun-08 jul-08 aug-08 sep-08
oct-08 nov-08 dec-08 jan-09 feb-09 mar-09 apr-09 may-09 jun-09 jul-09 aug-09 sep-09



Irrigation return flow (mm)
Measured
Simulated
CALIBRATION
VALIDATION
NO_3-N in irrigation return flow (kg ha^{-1})
100
80
60
40
20
0
6
5
4
3
2
1
0
oct-05 nov-05 dec-05 jan-06 feb-06 mar-06 apr-06 may-06 jun-06 jul-06 aug-06 sep-06 oct-06 nov-06 dec-06 jan-07 feb-07 mar-07 apr-07 may-07 jun-07 jul-07 aug-07 sep-07
oct-07 nov-07 dec-07 jan-08 feb-08 mar-08 apr-08 may-08 jun-08 jul-08 aug-08 sep-08



CALIBRATION
VALIDATION
Measured
Simulated
Irrigation return flow (mm)
NO3-N in irrigation return flow (kg ha-1)
0
10
20
30
40
50
0
2
4
6
oct-06
nov-06
dec-06
jan-07
feb-07
mar-07
apr-07
may-07
jun-07
jul-07
aug-07
sep-07
oct-07
nov-07
dec-07
jan-08
feb-08
mar-08
apr-08
may-08
jun-08
jul-08
aug-08
sep-08
oct-08
nov-08
dec-08
jan-09
feb-09
mar-09
apr-09
may-09
jun-09
jul-09
aug-09
sep-09



Improved fertilization
Improved irrigation
Improved fertilization and irrigation
Current
NO3-N load in irrigation return flow (kg ha-1)
NO3-N concentration in irrigation return flow (mg L-1)
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
16
18
oct-05
nov-05
dec-05
jan-06
feb-06
mar-06
apr-06
may-06
jun-06
jul-06
aug-06
sep-06
oct-06
nov-06
dec-06
jan-07
feb-07
mar-07
apr-07
may-07
jun-07
jul-07
aug-07
sep-07
oct-07
nov-07
dec-07
jan-08
feb-08
mar-08
apr-08
may-08
jun-08
jul-08
aug-08
sep-08